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MODEL BASED STRUCTURAL EVALUATION & DESIGN OF OVERPACK CONTAINER FOR BAG-BUSTER PROCESSING OF TRU WASTE DRUMS[1]

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ABSTRACT

This paper describes a materials and computational model based analysis utilized to design an engineered "overpack" container capable of maintaining structural integrity for confinement of transuranic wastes undergoing the cryo-vacuum stress based "Bag-Buster" process and satisfying DOT 7A waste package requirements.

The engineered overpack is a key component of the "Ultra-BagBuster" process/system being commercially developed by UltraTech International for potential DOE applications to non-intrusively breach inner confinement layers (poly bags/packaging) within transuranic (TRU) waste drums. This system provides a lower cost/risk approach to mitigate hydrogen gas concentration buildup limitations on transport of high alpha activity organic transuranic wastes.

Four evolving overpack design configurations and two materials (low carbon steel and 300 series stainless) were considered and evaluated using non-linear finite element model analyses of structural response. Properties comparisons show that 300-series stainless is required to provide assurance of ductility and structural integrity at both room and cryogenic temperatures.

The overpack designs were analyzed for five accidental drop impact orientations onto an unyielding surface (dropped flat on bottom, bottom corner, side, top corner, and top). The first three design configurations failed the bottom and top corner drop orientations (flat bottom, top, and side plates breached or underwent material failure). The fourth design utilized a protruding rim-ring (skirt) below the overpack's bottom plate and above the overpack's lid plate to absorb much of the impact energy and maintained structural integrity under all accidental drop loads at both room and cryogenic temperature conditions. Selected drop testing of the final design will be required to confirm design performance.

INTRODUCTION

A relatively small but very significant portion of the transuranic wastes within the U.S. Department of Energy (DOE) complex is not considered to be transportable to the designated repository (WIPP) because of excessive hydrogen generation rates. For these wastes, high alpha activity radiolysis of organic waste materials will lead to exceeding allowable maximum accumulated hydrogen (flammable gas) concentration limits established for waste payload containers (drums) in the Transuranic Package Transporter, Model II (TRUPACT II transporter).

Manually intensive repackaging is the current baseline approach planned to bring these wastes into compliance for transport to WIPP. Repackaging requires opening the high activity Pu-238 drums, un-packaging the wastes, and redistributing them into new containers in smaller activity quantities. The DOE has been conducting developmental evaluations of various potential alternative technology based approaches to reduce the costs and risks involved in baseline repackaging. Among them is the "Ultra-BagBuster" technology which uses a liquid nitrogen based cryogenic cooling and vacuum induced pressure differential/stress approach to in-situ breach the multiple layered poly waste bags/packages within a waste drum. Breaching the inner confinement layers can reduce the buildup of radiolytic hydrogen

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concentrations to levels allowing for shipment with current licensed transport methods.

To perform the "Ultra-BagBuster" bag-breaching process the waste drum is first enclosed in an engineered overpack. The overpack lid includes special mechanical means for performing, insitu, a two-inch diameter "hole-saw" penetration of the contained waste drum lid and inner hard poly liner. The overpack lid assembly also contains a specially designed HEPA grade filter, vacuum lines, and connection valves which attach to an external vacuum pump system and allow for rapid evacuation of the over-pack and waste drum. When the overpacked waste drum and contents are to be processed, the overpack will be placed in a liquid nitrogen-cooled conditioning chamber that will lower the temperature of the overpack contained waste drum contents to -300^{o}F and then rapidly evacuate the overpack and drum to more than 12 psig vacuum (less than 2.7 psia) in order to breach the embrittled poly waste bags within the drum. The engineered overpack is then removed from the conditioning chamber for later handling and transport to WIPP as the filtered waste payload container (primary confinement).

The overpack must withstand the cryo-vacuum processing cycle conditions and also meet the operational handling and drop-load test requirements of DOT-7A type A packaging (Reference 1). The engineered overpack must withstand potential handling/drop impact conditions at both cryogenic and room temperatures.

This paper presents the model based structural analysis of the engineered overpack, which was a key part of an overall independent engineering test and analysis based evaluation of the developing bag-buster process technology conducted by the INEEL.

OVERPACK STRUCTURAL EVALUATION

A structural evaluation adhering to the requirements of "DOE/RL-96-57: "DOT Specification 7A Type A Packaging," was performed on the Bag Buster Overpack throughout its design phase. The overpack is being designed and fabricated by Ultra Tech International of Jacksonville, Florida. It is the intent of Ultra Tech to have this overpack used in the DOE complex.

The overpack will be used to process and transport 55-gallon drums of radioactive waste for the U. S. Department of Energy. When the drums and their contents are being processed, the overpack will be placed in a liquid nitrogen conditioning chamber that will lower the temperature of the overpack and its contents to -300^{o}F.

Structural requirements satisfying DOT 7A Type A Packaging include applying loading conditions that reflect test requirements for a free drop test, penetration test, static lift condition, and stack test, for the new overpack design. This paper focuses on the free drop test requirement from the overpack's structural evaluation.

Overpack Design Configurations

The waste drum overpack is basically comprised of four components: a bottom (or body), lid, mating flange, and attachment bolts. The bottom and lid components of the overpack are steel sheets formed into cylinders (bottom: 25-inch diameter x 30-inch length, lid: 26-inch diameter x 7-inch length) with one end closed and the other bound by circular rings. The rings are flanges that have grooves for two o-rings. The top and bottom components are bolted together through the mating flange, forming a sealed cavity.

The final design for the overpack evolved through four design configurations. Structural evaluations were performed for each design configuration and evaluation results provided recommendation basis for each new design concept. Figure 1 illustrates the four overpack design configurations evaluated.

Design 1 consisted of an overpack fabricated entirely from steel plate, sheet, and bolt materials. The bottom of the overpack and top of the lid were rounded. An exterior flange was utilized to mate the overpack lid and bottom. For lifting and handling, closed loop lugs were used for both the lid and for the entire overpack assembly.

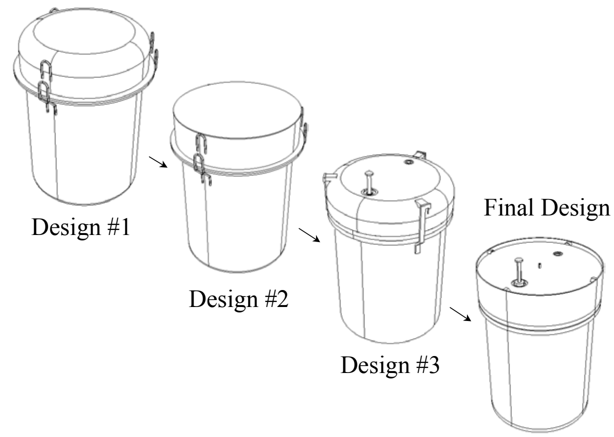

Figure 1. Hiddle line model representation of evaluated overpack design configurations.

Design 2 was identical to Design 1, except the rounded corners were replaced with straight corners.

Design 3 consisted of an overpack fabricated with a right circular cylinder bottom and a rounded top lid. Additionally, details for an underside filter, vacuum connection, and a drum penetrator saw were added to the rounded lid. (The lid details were designed to allow waste drum penetration by the saw and cavity gases filtered and extracted through the vacuum connection). The flange was also changed to be flush with lid's side. For lifting and handling, open loop stepped hook lugs were included for handling the entire overpack assembly and inverted light gage channels were provided for handling the lid.

Design 4 (or final design) consisted of an overpack fabricated with a right circular cylinder bottom and lid with extended skirting above and below the overpack ending plates. The added skirting was specifically designed to absorb energy and be sacrificed while maintaining package containment, in the event of an accidental drop. As in Design 3, the flush flange design was preserved. A new lifting lug for overpack handling was employed on the lid's top surface.

Free Drop Test

The specimen (overpack containing 55-gallon waste drum) is dropped from a height of 4 feet onto a target so as to suffer the maximum damage to the safety features being tested. The target surface is a flat horizontal unyielding surface. This test condition involves several orientations of the overpack when it makes contact with an unyielding surface. Orientations include flat bottom and top drops, side drop, and corner drops, as shown in Fig. 2

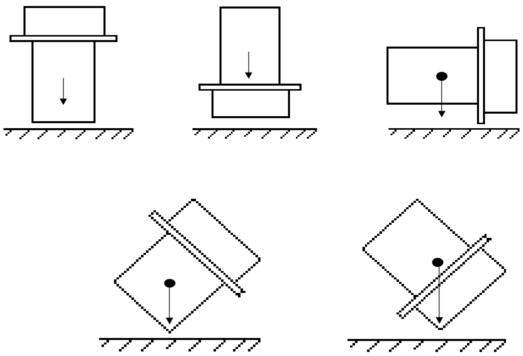

Figure 2. Free drop test orientations shown.

The qualification drop tests occur at room temperature. However, due to the cryo-processing with which the overpack is involved, a drop of the overpack could also occur at –300°F when the overpack is removed from the liquid nitrogen conditioning chamber and moved to a staging location. This condition was encompassed in the analytical evaluation.

Overpack Material Selection

At the supplier's request, two steel material types (i.e., low carbon steel grades and 304 stainless steel) were considered for the overpack's plate and sheet fabrication. The supplier wanted to fabricate the overpack (if possible) with a less expensive low carbon steel grade material. The overpack will be exposed to temperatures ranging from room temperature (68°F) through –300°F and will be susceptible to a potential drop at any temperature within this range. Figures 3, 4, and 5, illustrate the material strength and ductility properties for selected low carbon steel grades and 304 stainless steel from room through cryogenic temperatures (References 2 and 3). The dotted vertical line (in each figure) crosses respective property lines for both material types at the overpack's lower boundary temperature (–300°F).

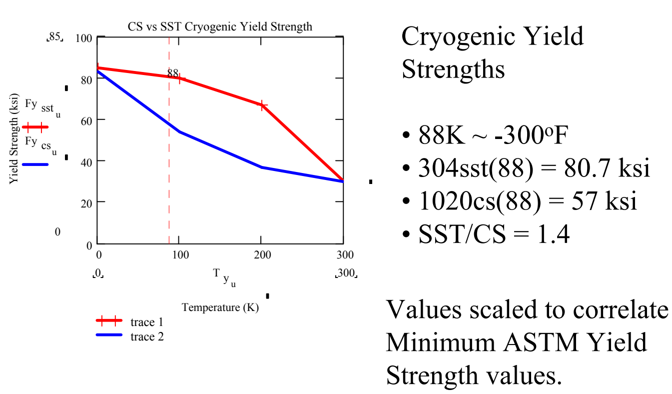

Figure 3. Material yield strengths for 304 stainless and low carbon steels shown from room to cryogenic temperatures.

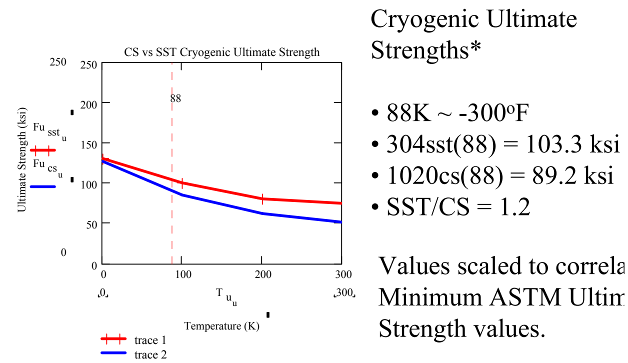

Figure 4. Material ultimate strengths for 304 stainless and low carbon steels shown from room to cryogenic temperatures.

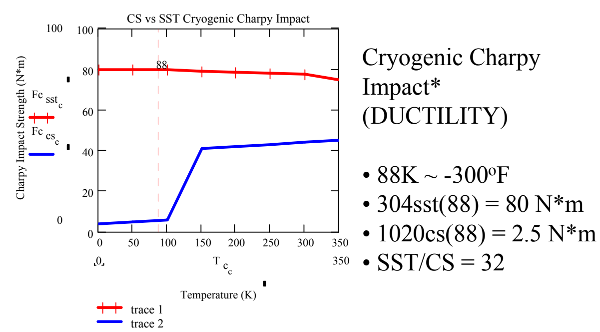

Figure 5. Charpy impact (ductility) values for 304 stainless and low carbon steels shown from room to cryogenic temperatures.

As illustrated, 304 stainless steel material strength and ductility properties increase as the temperature decreases. The ductility of 304 stainless steel at low temperatures remains favorable, whereas low carbon steel exhibits brittle behavior as the temperature is lowered. Carbon steel will not provide the required structure reliability at the overpack's lower temperature limit (-300°F). This is due to its well known ductile-brittle transition temperature (approximately –190°F). Therefore, 304 stainless steel must be used for packages with low temperature ductility requirements.

Also noted is that 304 stainless steel is at its weakest condition and is most susceptible to material failure at room temperature. Therefore, all overpack design configurations were analyzed with 304 stainless steel material properties at room temperature (68°F). If the overpack is structurally acceptable at room temperature, it will also be structurally sound at lower temperatures. Table 1 compares material properties at room temperature between four steel grades considered for overpack fabrication. Minimum ASTM material strength and strain values (at room temperature) are listed .The 304 stainless steel and low carbon steel grades were considered for overpack plate and sheet fabrication (References 4, 5, 6, and 7). Nitronic 60 and 304 stainless steel grades were used for bolting materials (Reference 8).

Table 1. Material properties at room temperature.

Material Property	304 SST	Nitronic 60 SST	A36 CS	A569 or A1011 CS
Youngs Modulus (ksi)	2.8E7	2.8E7	3.0E7	3.0E7
Poisson's ratio (in/in)	0.29	0.29	0.292	0.292
Mass density (lb/in^3)	0.29	0.29	0.283	0.283
Eng. Yield Strength (psi)	30,000	50,000	36,000	30,000
Eng. Ultimate Strength (psi)	75,000	95,000	58,000	52,000
Eng. Ultimate Strain (%)	0.30	0.35	0.20	0.25
True Yield Strength (psi)	30,031	50,089	36,043	30,030
True Ultimate Strength (psi)	97,500	128,250	69,600	65,000
True Plastic Strain (%)	0.261	0.298	0.181	0.222

Evaluation

Several finite element models (FEM) were used to evaluate the four overpack design configurations. Each FEM shared common component characteristics (i.e., bottom, lid, flange, bolts, etc.). Specific design features were then incorporated for each design configuration.

The finite element models were created using SDRC I-DEAS software (Reference 9) and then converted to a format compatible with ABAQUS/Explicit (Reference 10). ABAQUS/Explicit was used to perform dynamic analyses and solve for nonlinear behavior including plasticity, geometric deformation, and interaction between contacting surfaces. Figure 6 shows the finite element mesh of Design 3, used as an example to depict similar FEMs for each design configuration.

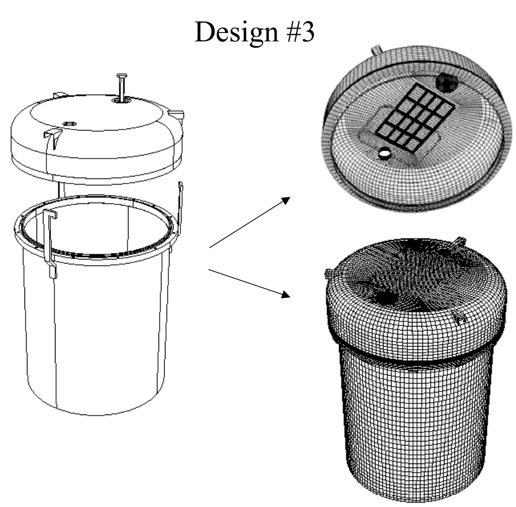

Figure 6. Typical solid model to FEM mesh conversion shown.

The overpack was designed for a snug fit between an actual waste drum and its interior cavity walls. The interaction between the overpack and its contents (i.e., a 55-gallon waste drum) was captured within the analysis. The waste drum was modeled as a solid right circular cylinder with its density adjusted to reflect the weight for a loaded drum. The solid drum mesh impacts the overpack's inner cavity in conjunction with the overpack's exterior impact onto an unyielding surface.

Acceptance criteria for the free drop test (as defined in DOT 7A Type A Packaging, Reference 1), shall be met by demonstrating that the overpack design does not incur a material failure or deformation that would create a breach between atmosphere (the outside of the overpack) and the interior of the overpack. Material failure, which does not compromise the interior of the overpack, is allowed. Emphasis is placed on the overpack's structure to insure containment of the waste, should the interior drum rupture within the overpack following a potential drop.

Failure of finite element analysis (FEA) elements for each evaluated design configuration was defined in terms of strain levels reached. Applying failure criteria in the ABAQUS/Explicit program imposed the failure definition. In each evaluation, failure at a point was assumed to occur when the equivalent plastic strain (PEEQ) reached the ultimate (or failure) strain of the material. Figure 7 shows the stress versus strain curve used by ABAQUS/Explicit to track element strain energy for each material type evaluated.

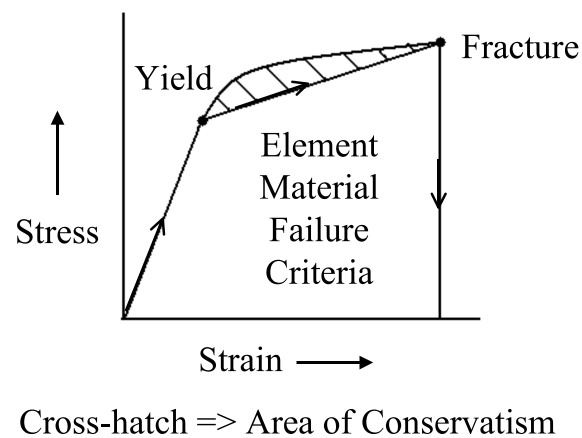

Figure 7. Stress verses strain curve depicting element material failure criteria.

As shown, the stress level reaches to yield point, then ramps to failure stress, and then drops to zero stress at failure strain. With this treatment, it is not necessary to compare calculated strains with allowable strains. Instead, any FEA element whose strain reaches the failure strain limit is effectively removed from the mesh. The failed element no longer contributes to the FEA model. Material failure is defined as occurring herein when the plastic equivalent strain exceeds 0.261 (or failure strain – see Table 1) in a 304 stainless steel element.

Overpack Free Drop Results. A common trend was illustrated between the first three overpack design configurations. Each withstood flat bottom and flat top drop impact orientations, but all had material failure (or containment compromise) with the corner drops. The external flange design feature (associated with Designs 1 and 2) compromised the o-ring flange seal in a side drop orientation, due to excessive deformation of the flange. The flush flange design feature of Design 3 eliminated this seal failure condition. Figures 8 through 10 illustrate FEA material failure results in overpack Designs 2 and 3 associated with corner drop orientations. All overpack drop results reflect material conditions at room temperature.

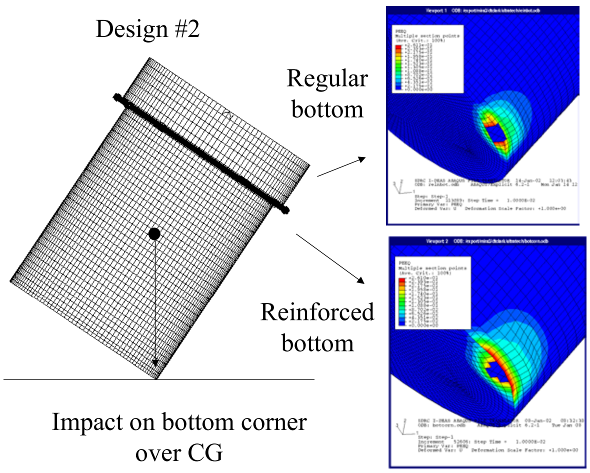

Figure 8. ABAQUS output showing material failure in bottom corner of Design 2.

Figure 8 shows material failure results for two variations of the Design 2 configuration. The lower picture inset shows material failure results when the Design 2 overpack is reinforced along its side with a thickened plate ring. In this variation, the overpack's side is stiffened and transmits impact loading to the overpack's bottom plate causing material failure and containment compromise.

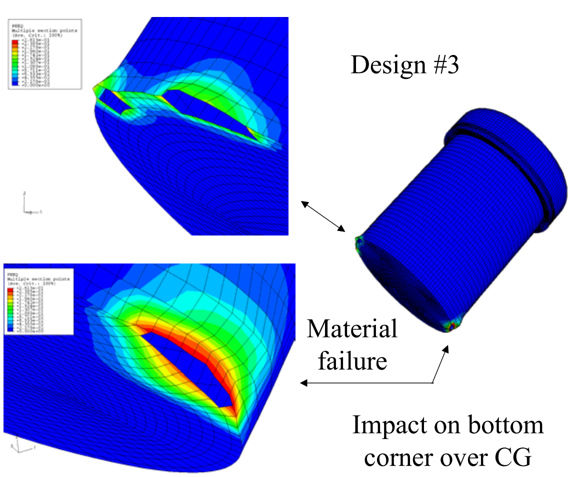

Figure 9. ABAQUS output showing material failure in bottom plate of Design 3.

Material failure occurs in the overpack's bottom plate and adjacent siding. The Design 3 (Figure 9) overpack's 3/8-inch plate is much stiffer than the adjoining 1/16-inch side, causing the impact forces to be transmitted to the opposite base plate side. The transmitted impact forces cause material failure at the base plate's furthest point from actual impact. The overpack's containment has been compromised.

Figure 10 shows that the lid is pried open when the Design 3 configuration is dropped on its top corner. This is a catastrophic breach of containment. After impact, the lid remains intact, even though the lid has been pried open. This implies that the lid is too stiff, which causes impact forces to be transmitted to the opposite side bolts and leads to subsequent overpack failure.

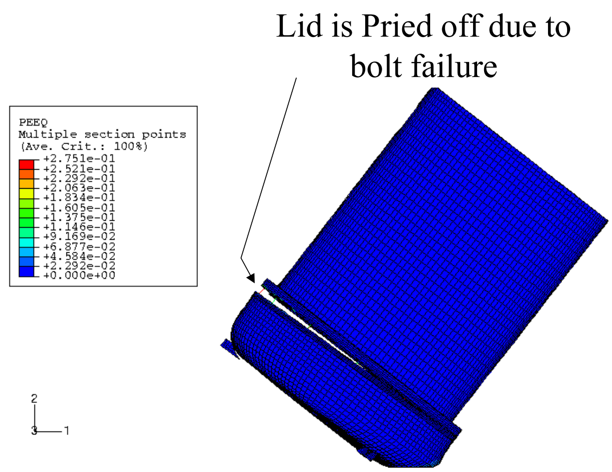

Figure 10. ABAQUS output shows bolt material failure for top corner drop orientation of Design 3.

Bolt failure (shown in Figure 10) reflects 304 stainless steel bolts (used to secure the overpack's flange connection), has exceeded its failure strain limit. Similar breach of containment results occur for this same drop orientation when increased strength Nitronic 60 stainless steel bolts (see Table 1) are used to secure the lid, except that the open gap is less pronounced (as shown in Figure 10).

Figures 11 and 12 illustrate FEA material failure results for overpack Designs 2 and 3 associated with side drop orientations.

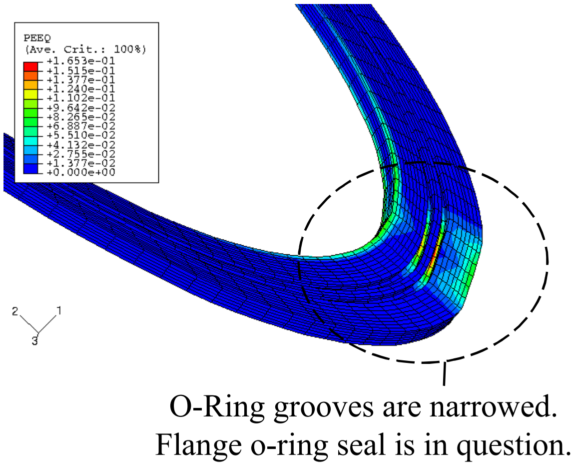

Figure 11. ABAQUS output shows deformed o-ring slots of flange component for side drop orientation of Design 2.

Figure 11 shows the side drop impact loading of the external flange feature (i.e., Designs 1 and 2) has greatly deformed the o-rings grooves, placing the overpack seal in question. The flush flange feature of overpack Design 3 eliminated this concern, by putting the flange to be flush with the lid's sides. The "flush flange" design feature significantly stiffened the lid component causing the lid to pry open due to attachment bolt material failure (as indicated in Figure 10).

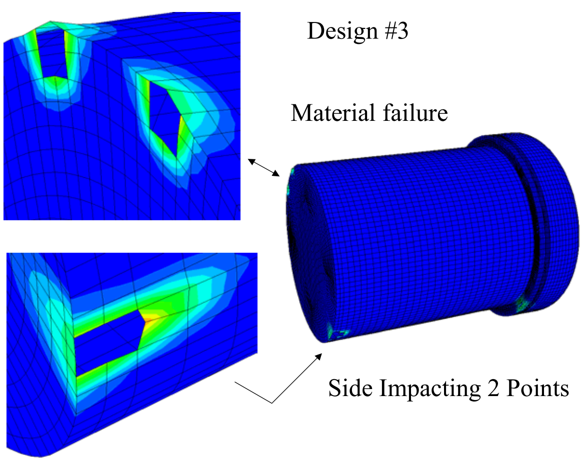

Figure 12. ABAQUS output showing material failure in bottom plate of Design 3 for side drop orientation.

Figure 12 shows material failure in the bottom front corner (i.e., contact area) and opposite corner of Design 3's bottom plate and adjacent sides. Similar to that of the lid, this implies that the overpack's bottom plate and mating sides are too stiff, which causes impact forces to be transmitted through the stiff bottom plate to the opposite side and leads to subsequent overpack failure.

Final Design Free Drop Results. A fourth design was considered that utilized a skirt that extended beyond the bottom and top ends of the overpack. The intent of the skirt design feature was to create a component of the overpack that could experience material failure and absorb energy sufficient to protect the more important containment portions of the overpack. Thus, the skirt feature could be sacrificed to preserve the overpack's containment components. Figure 13 illustrates the extended skirt design feature of Design 4's overpack configuration.

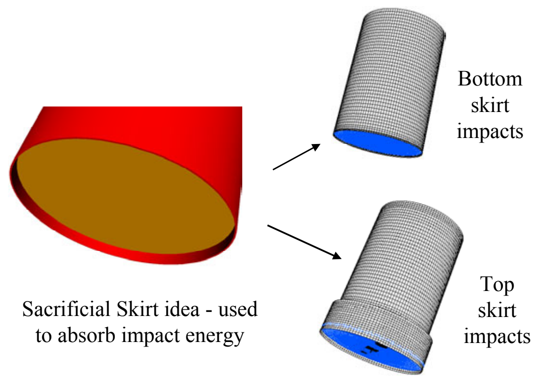

Figure 13. Solid model and FEM meshes used to evaluate the sacrificial skirt feature of the final design.

The skirt feature of Design 4 performed as expected for all drop orientations (i.e., vertical, corner, and side). Figure 14 illustrates FEA results for the final overpack design for worst-case corner drop orientations showing maximum material deformation and failure.

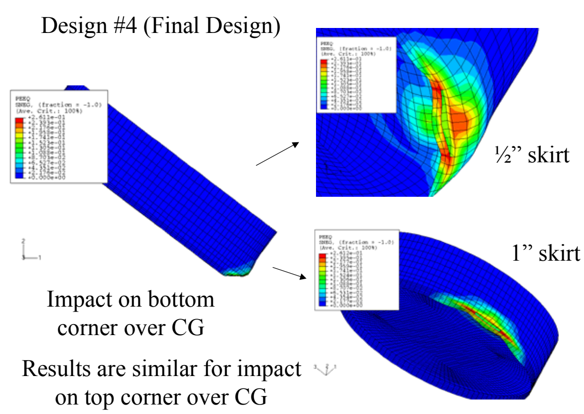

Figure 14. Bottom skirt model after impact on corner shows material failure in skirt area.

The overpack skirt component is sacrificed to protect the overpack's containment components from breaching. The skirt design feature acts as an impact limiter and absorbs much of the impact energy that would normally be directed to the overpack's containment components. Figure 14 shows FEA results for varying length skirts. The 1-inch skirt length provided marginal improvement (i.e., less plastic equivalent element strain) over the ½-inch skirt length component. Similar results were demonstrated for a top corner drop. The top skirt created a less-stiff lid and maintained the o-ring seal between the bottom and lid overpack components.

The Design 4 overpack skirt design feature was examined for low carbon steel materials to evaluate if it was an option for ambient temperature handling and could be used to fabricate the overpack test specimens. Material strength and strain properties used in the low-carbon steel drop evaluations are reflected in Table 1. Figure 15 illustrates the skirt results for 304 stainless and low carbon steel overpack fabrications.

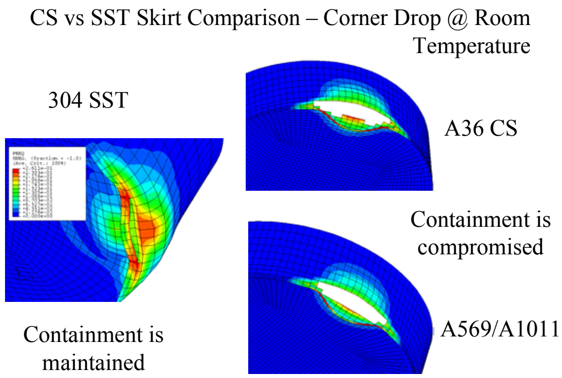

Figure 15. Extended skirt material comparison drop results illustrated for 304 stainless and low-carbon steels.

Figure 15 shows that the 304 stainless steel skirt maintains overpack containment and is required with use of extended skirts. The low carbon grade materials considered for potential room temperature handling (or for testing) should not be used. Hence the final design utilizes Design 4 skirt features coupled with 304 stainless steel material fabrication.

CONCLUSION

Engineering reviews and computational model based structural analyses of the drum over-pack design led to several recommendations for design improvements. A "must use" recommendation is to build the over-pack of 304 stainless steel to assure ductility and integrity of the container during and after the cryo-processing conditions. Carbon steel, although less expensive, cannot be used due to complete loss of ductility at the cryo-temperatures required for the bag-breaching process. Brittle strength/fracture properties of carbon steel at cryo-temperatures lead to the potential for brittle cracks/micro-fracturing, and un-reliable strength/failure properties for the over-pack. The over-pack becomes the primary confinement layer for a processed drum with breached bags of transuranic wastes, and must be assured by design and validated by test to maintain structural integrity and properties that can accommodate potential subsequent waste package handling loads in transport and disposal.

Based upon the structural and material evaluations, the overpack's final design is predicted to pass the testing mandated by DOE/RL-96-57, "Test and Evaluation document for DOT Specification 7A Type A Packaging." Furthermore, the conditions analyzed provide conservative results with respect to the structural performance of the stainless steel overpack during cryo-processing, as well as for its operational handling temperature conditions.

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